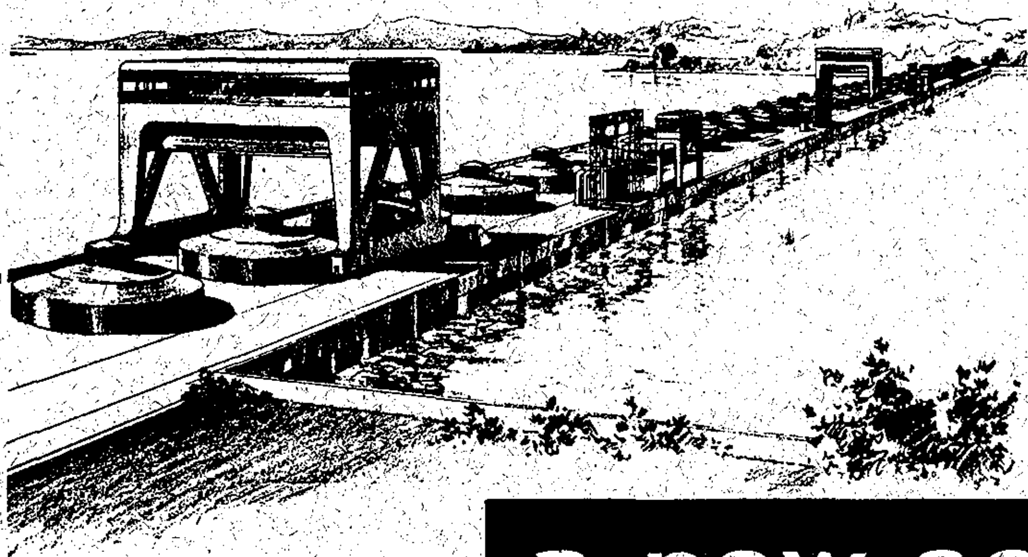
PASSAMAQUODDY

TIDAL POWER



a new source of energy

Address by
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Presented at the Annual Meeting
of the American Society of Civil Engineers,
New York City, N.Y.
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ARMY-NED-BOSTON

PASSAMAQUODDY TIDAL POWER: A NEW SOURCE OF ENERGY[a]

Alden K. Sibley[1]

SYNOPSIS

Generation of electric power from the tides in the Bay of Fundy has intrigued engineers for four decades. A $3,300,000 engineering investigation of the Passamaquoddy Tidal Power Project near Fundy's mouth, inaugurated three years ago by the Canadian and United States governments, is now nearing completion. Recommendations to the governments of the feasibility of the project will be made by the International Joint Commission[2] from the conclusions of its Engineering[3] and Fisheries Boards.[4]

The U. S. Army Engineer Division, New England, through the Passamaquoddy Survey Division,[5] is conducting the engineering investigations in collaboration with the Federal Power Commission, the New Brunswick Electric Power Commission, the Department of Public Works and the Department of National Resources and Northern Affairs of Canada, and other agencies of the State of Maine and of the provincial and federal governments.

a. Paper presented at the Annual Meeting of the American Society of Civil Engineers, N.Y., October 14, 1958.
1. Brig. Gen., Div. Engr., U.S. Army Engr. Div., New England.
2. Chairmen: U.S. Section, The Honorable Douglas McKay; Canadian Section, General A.G.L. McNaughton.
3. Chairmen: U.S. Section, Lt. Gen. Samuel D. Sturgis, former Chief of Engineers, U.S. Army; Canadian Section, Mr. Gerald Millar, Chief Engineer, Harbours and River Engineering Branch, Dept. of Public Works, Canada.
4. Chairmen: U.S. Section, Dr. D.L. McKernan; Canadian Section, Dr. J.L. Hart.
5. Under direction of Mr. Richard D. Field, Chief, Passamaquoddy Survey Division.

Following a brief assessment of the world energy problem, this paper summarizes the progress of the Passamaquoddy Survey thus far, including field investigations, analyses of single and two pool methods of harnessing the tides, adoption of the project plan and determination of its structural components, investigation of auxiliary methods to stabilize the variable tidal power output, and the problems of economic evaluation of the project.[1]

In view of the fact that many aspects of the tidal power survey have not yet been reviewed by members of the Passamaquoddy Engineering Board and Committee nor considered by the International Joint Commission, the writers present summary of the progress of the three year study should not be construed as pre-judging any of its specific findings or general conclusions.

INTRODUCTION

The world's ever-increasing consumption of power calls for a serious appraisal of all potential energy sources. Although harnessing the tides could produce but a fraction of the next decade's power requirement, the Passamaquoddy studies symbolize today's search for new sources of power to meet tomorrow's demands. Our own

1. The writer is grateful for the assistance and suggestions by individual members of the U.S. and Canadian agencies referred to in the synopsis; to the National War College, Washington, D.C., for permission to use material from several lectures by the writer as a former member of the faculty; and to J. Carlton Ward, President of the Vitro Corporation of America, New York City, N.Y., for data used in the introductory discussion of the world energy problem.

survival as a free nation and that of the free world may well depend on the vision and skill with which we meet our power needs in the next decade. Total hydroelectric power capacity in the Soviet Union installed since the shambles of World War II now approaches that in this country. Of the 17 dams programmed for the Volga, one alone at Stalingrad with power-on-line scheduled this year (1958) will have an installed capacity of 2.3 million kilowatts, about 18 percent larger than that of Grand Coulee. Khruschev's announcement in August, 1958, indicates that power development: thermal, hydro and nuclear, including three mammoth hydro plants of from 3 to 5 million kilowatts of installed capacity under way in Siberia - has high Soviet priority. Energy sources have become prime objectives in the cold war. The European economy and the NATO Alliance itself rely heavily on Middle East oil, and international relations are increasingly conditioned by control of power resources.

In 1910, the 100 million people of the United States produced 100 billion dollars worth of goods and services (fig. 1).[1] The gross national product has shot up out of all proportion to population growth until in 1957 it hit the $400 billion mark. Extended, the curve is roughly exponential while the population curve shows only an arithmetic increase. Plotted as GNP per capita the curve

1. Source: Vitro Corporation of America, New York City, N.Y.

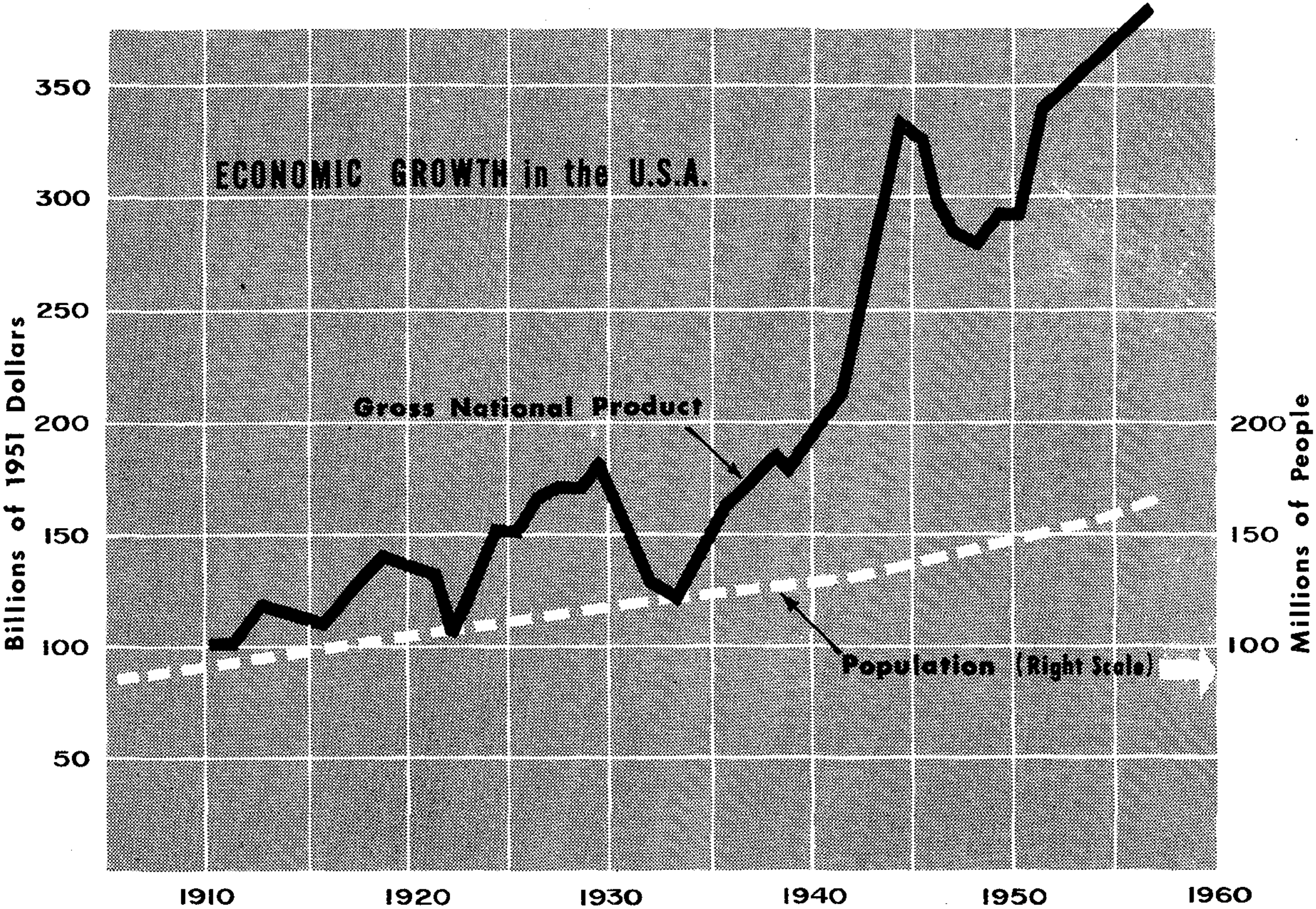
ECONOMIC GROWTH in the U.S.A.
Gross National Product
Population (Right Scale)
Billions of 1951 Dollars
Millions of People
350
300
250
200
150
100
50
200
150
100
1910
1920
1930
1940
1950
1960

Figure 1

approximates the growth of our standard of living. On what foundation does this exponentially expanding $400 billion standard of living rest? The answer emerges if we quite independently plot per capita power production in megawatt hours per man per year over the same time period and observe the startling correlation between the two curves which appears (fig. 2).[1] The significance is evident: our priceless heritage of social and economic progress is irrevocably tied to the use of energy in ever increasing amounts. The Federal Power Commission expects our use of power by 1980 to be four times present consumption. This would conform generally to an extrapolation of the exponential experience curve of figure 2. In ten, fifty or one-hundred years, to maintain the progress which we have come to think of as inherent in the American way of life, we shall evidently need to consume a staggering amount of energy. Where shall we find it?

ENERGY SOURCES

The center of our planetary system, the sun, which astronomers rate as a medium-sized Class G star, was considered the source of all forms of energy on earth. There are, however, sources of energy other than the sun's rays: energy locked in the atoms of the earth, and

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1. Source: Vitro Corporation of America, New York City, N. Y.

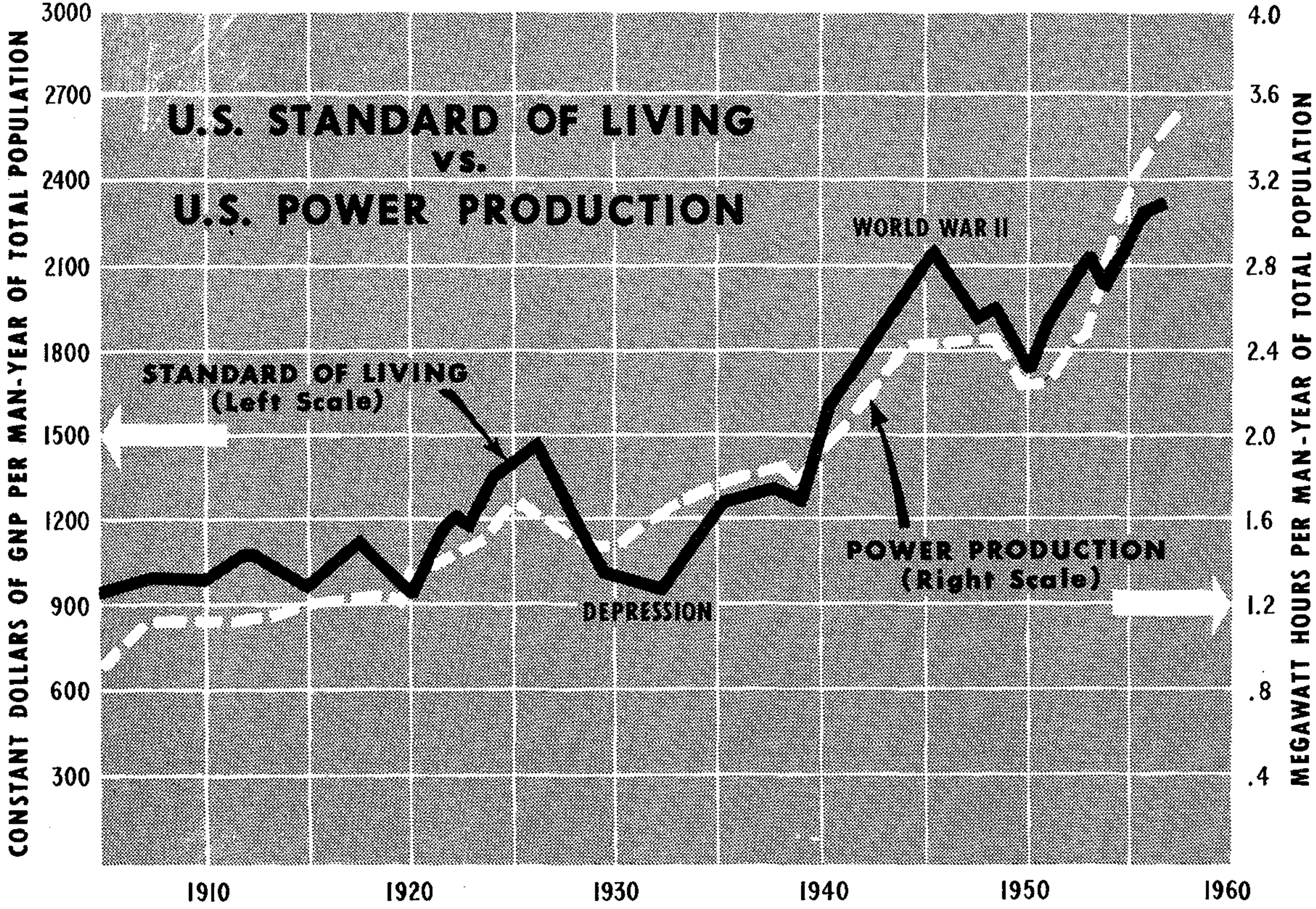

U.S. STANDARD OF LIVING
vs.
U.S. POWER PRODUCTION
CONSTANT DOLLARS OF GNP PER MAN-YEAR OF TOTAL POPULATION
MEGAWATT HOURS PER MAN-YEAR OF TOTAL POPULATION
3000
2700
2400
2100
1800
1500
1200
900
600
300
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
1910
1920
1930
1940
1950
1960
STANDARD OF LIVING
(Left Scale)
POWER PRODUCTION
(Right Scale)
WORLD WAR II
DEPRESSION

Figure 2

the energy of the earth's satellite, the moon. Conventional sources of energy today are mainly hydraulic power from our rivers and streams and chemical combustion of the fossil fuels - coal, oil and natural gas - energy of the sun stored millions of years ago. With the advent of the nuclear age, with the explosive proof of Einstein's formula $E = mc^2$, which postulates that mass and energy are interconvertible, we now find that we are able to unleash, through the processes of nuclear fission and fusion, a second source of energy stored from the beginning of time in the very building blocks of the universe itself: the atoms. A third great source of energy relatively undeveloped by man thus far is that of the rise and fall of ocean tides as the moon swings around us. Although cold and lifeless, the moon is so near to the earth that its gravitational pull on the waters of the seas produces mechanical energy, dissipated continuously in friction estimated at the rate of 2 billion horsepower.

The sources of energy in the United States have changed gradually over the past 100 years. The top line of figure 3 represents 100% of the energy consumed in the year indicated.[1] Contributions from the various energy sources are shown by the curves beginning with wood energy at the bottom, anthracite coal, bituminous coal which peaked in 1910, oil which was negligible before 1890, gas which came in even

1. 1953 Annual Report of the Twentieth Century Fund.

conventional energy resources will be exhausted by 1968, because the

ENERGY OUTPUT BY SOURCES IN THE U.S. (1850-1950)

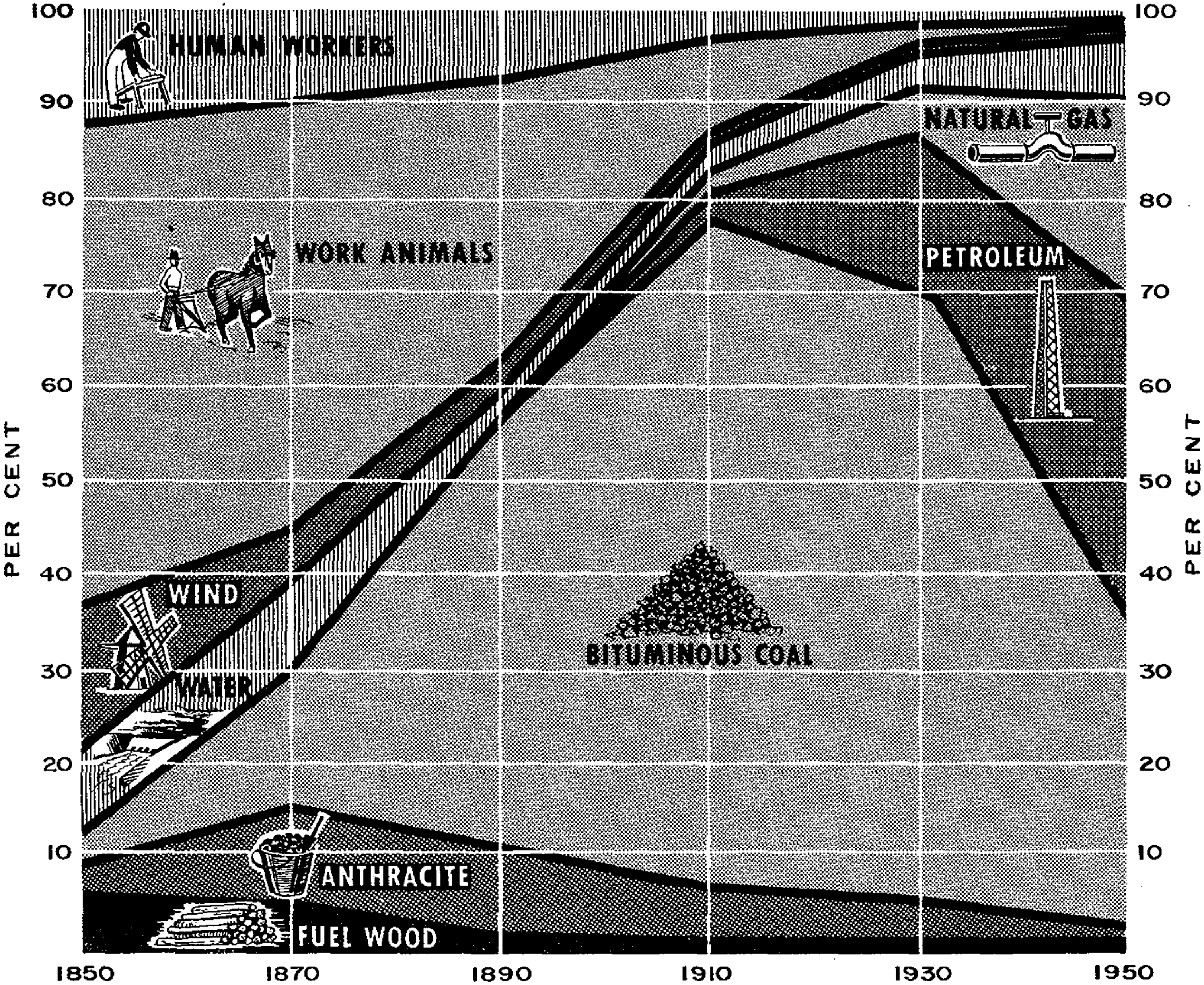


Figure 3

ENERGY REQUIREMENTS AND FUEL SOURCES

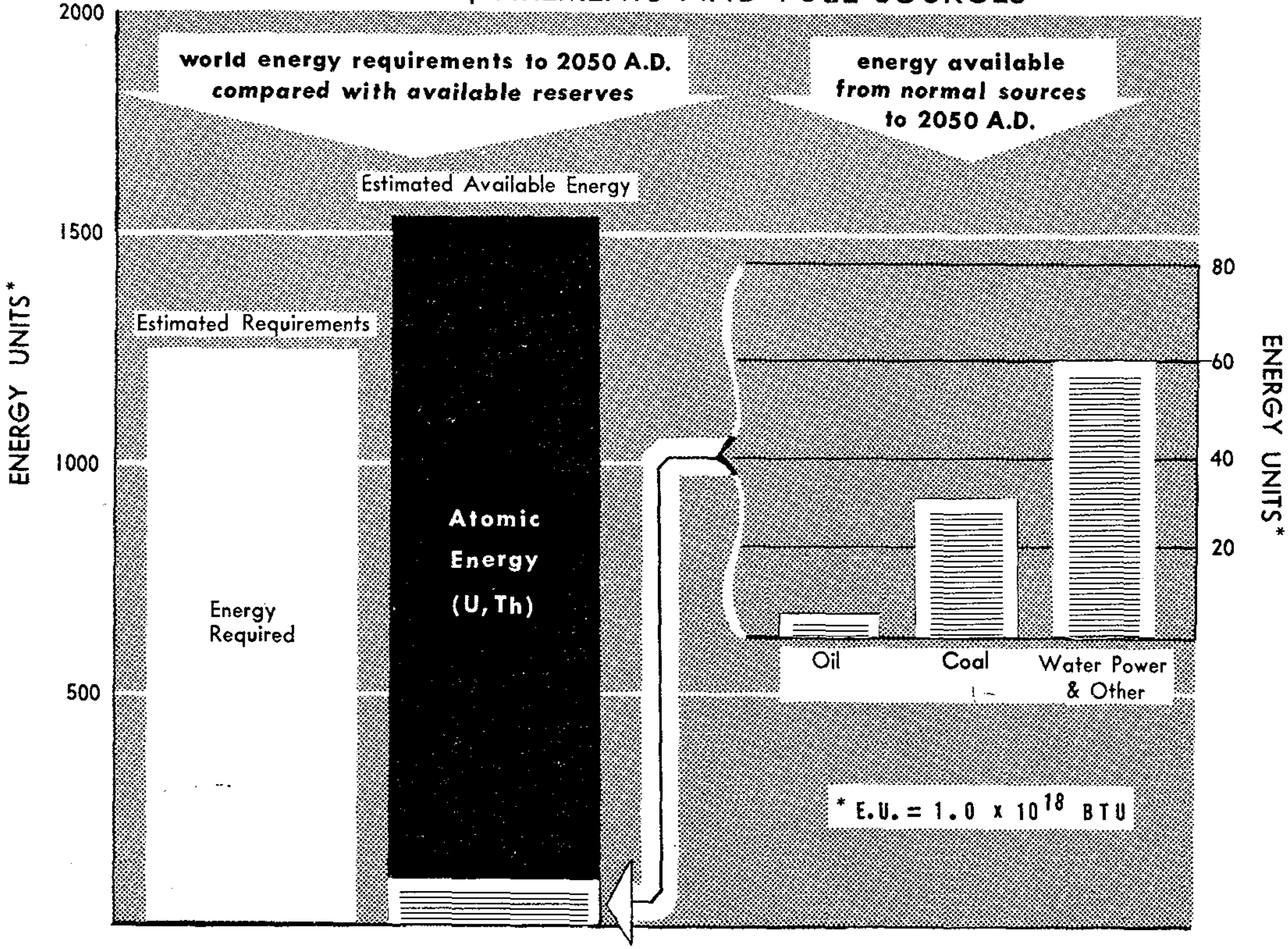


Figure 4

next 100 years, less than a 10-year supply is available from known conventional sources in the world. And if we are prodigal in burning up our fossil fuels for energy, there will be little left for the vital chemical processes on which we have come so largely to depend.

But this is only part of the picture. A few pioneering and federally subsidized industries are building nuclear power plants in this country and abroad. In Shippingport, Pennsylvania, an atomic power plant owned jointly by the Atomic Energy Commission and the Duquesne Light Company is now generating power for the City of Pittsburgh. The Yankee Atomic Electric Company, a pioneering group representing a pool of New England utility companies, is constructing a pilot reactor in the town of Rowe in northwestern Massachusetts. It is significant that this group of far-sighted engineers and businessmen feel that highly industrialized but relatively fuel-poor New England will be the first area in the United States where nuclear power will become economically competitive with 8 mill thermal power. Coal-hungry England, with 12 mill thermal power, inaugurated in the fall of 1956 the world's first full-scale atomic power plant at Calder Hall, Cumberland. The Calder Hall Station, which produces about 75,000 kilowatts (enough to supply a city of 200,000) is the first reactor of a United Kingdom nuclear power program of five million kilowatts by 1965. The United States, on the other hand, burning up fossil fuel resources at far cheaper rates, lags in development of nuclear power. When nuclear fission power is seriously developed, however, the world's known deposits of uranium and thorium will be adequate for the next 100 years with a little to spare. But what then?

With the coming exhaustion of fossil fuels and the limitation of uranium and thorium, man must look elsewhere. Where should he look? When faced with such a dilemma, man's age-old solution has been to look to the heavens.

In 1938 an astrophysicist, Hans Bethe, at Cornell University, solved the mystery of the source of the sun's energy by showing that it comes from burning hydrogen atoms into helium through a process called the "Carbon Cycle." In "Operation Greenhouse" on the Eniwetock Atoll in 1952, a group of dedicated AEC scientists led by Norris Bradbury, Edward Teller and Alvin Graves succeeded in making enough heat with an ordinary atomic fission explosion to burn a container of hydrogen isotopes into helium for the first time on earth. With the proper hydrogen isotopes plentiful enough in sea water for a pound of heavy water to sell for about twenty-eight dollars, a cheap and almost limitless supply of energy exists - theoretically enough to run the world for the next 10,000 years.[1]

1. The energy of 1 pound of heavy water is equivalent to that of of 2,500 tons of coal.

The intense heats of the fission explosion, however, which succeeded in fusing the light isotopes of hydrogen, lasted only a fraction of a microsecond. The problem of sustaining heats and pressures comparable to those in the central regions of the sun seems almost insurmountable on earth. Thus, perfection of a sustained thermonuclear reaction for production of useable energy remains one of today's greatest challenges to science. Sir John Cockroft of Britain's Atomic Energy Authority is attacking the problem with his "Zeta" (zero-energy thermonuclear assembly). The Second International Atoms for Peace Conference in Geneva last month (September, 1958) saw the unveiling of such devices as Scylla, DCX, Stellerator, and the Astron developed in such U. S. programs as Project Sherwood. Soviet scientists, devoting their best efforts to this problem, have developed an enormous device called Ogra. The sustained thermonuclear reaction may well be the solution to the world's future energy needs. But in spite of the recognized urgency of this problem and today's crash programs to solve it, the finest and most optimistic of the world's scientific minds do not anticipate an early solution.

What other possibilities appear as we turn our eyes again toward the heavens? Our natural sputnick, the moon, with a mass about 1/81 of that of the earth and revolving in an orbit at a mean distance of only ten times the earth's circumference, causes tidal movements of our oceans, a source of energy that man thus far has failed to harness. In an era when the need for energy has never been so great, nor the exhaustion of conventional sources of fuel so imminent, man can scarely afford not to examine all possible source of power.

SUN, EARTH, MOON, AND THE TIDES

Although the science of tidal physics can be enormously complicated, in its barest essentials it is relatively straightforward. To simplify the theory of the sun - earth - moon relationships and resulting gravitational effects upon the oceans of the earth, let us assume that the earth is covered by a uniform envelope of very deep water. From the inverse square law of classical Newtonian mechanics, gravitational attraction between two bodies increases as the square of the distance between them decreases (fig. 5 - diag. 1). Thus the moon pulls the water nearest to it with greatest force, the solid earth with somewhat less force, and the water on the far side of the earth with least force, in effect pulling the water on the side nearest the moon, as well as on the side farthest from it, away from the earth. This gravitational pull of the moon would thus tend to distort our hypothetical water envelope into a football-shaped mass of water, or prolate ellipsoid of revolution surrounding the solid earth core, with the long axis of the football always pointing toward the moon. Since the earth is about 24,000 miles in circumference, and since it rotates on its axis once every 24 hours, the solid earth carrying its water blanket would spin around inside of this hypothetical, football-shaped wave configuration from west to east at a velocity of about 1,000 miles an hour at the equator. To an observer standing on the equator, the ends of this water football would appear as two huge tidal waves passing over him from east to west at 1,000 miles an hour at intervals of 12 hours and 25 minutes. Since wave velocity depends on depth of water, this speed would require oceans 13 miles deep. However, the oceans are in fact only deep enough to permit wave velocities about half this great. Consequently, instead of a single water football pointing toward the moon, we find the shallow seas pulled into a succession of water footballs tumbling end over end as they are carried around by the earth's rotation. The ends of these water footballs thus form a succession of waves which combine to form a wave group having a velocity compatible with the actual depths of the oceans of the earth. The group velocity of the waves, like the motion of a clock pendulum, is a phenomenon of resonance. At the instant when the forces acting on a resonant system are maximum, the position or configuration of the system is always exactly opposite that toward which these forces are pulling it. For example, the simple pendulum is always at the extreme right end of its swing at the instant the tangential component of gravitational force exerts its maximum pull to the left. So it is with the water envelope around the earth, which in fact assumes a

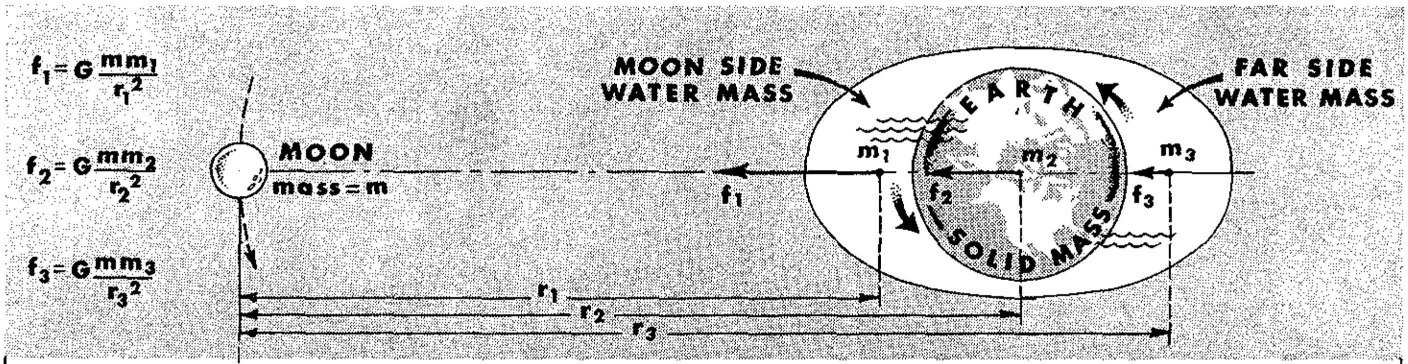


Diagram 1. **HYPOTHETICAL DEEP OCEAN "FOOTBALL"**

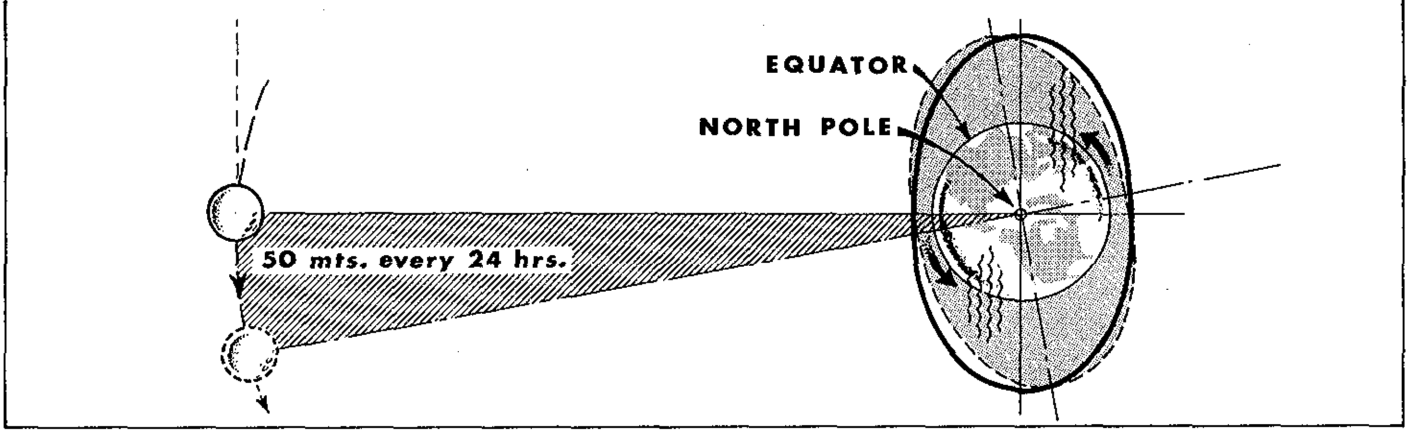


Diagram 2. **SHALLOW OCEAN "SQUASHED ORANGE"**

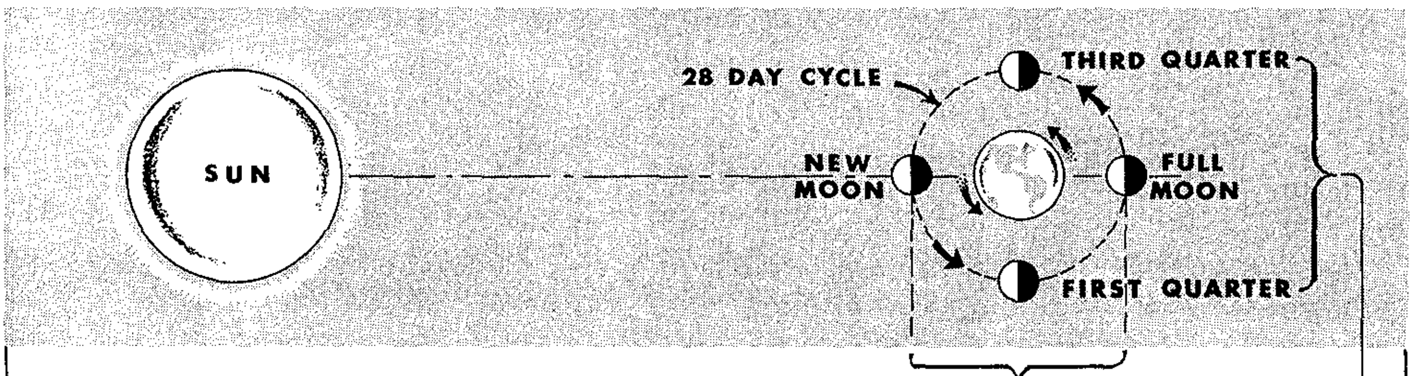


Diagram 3. **PHASES OF THE MOON**

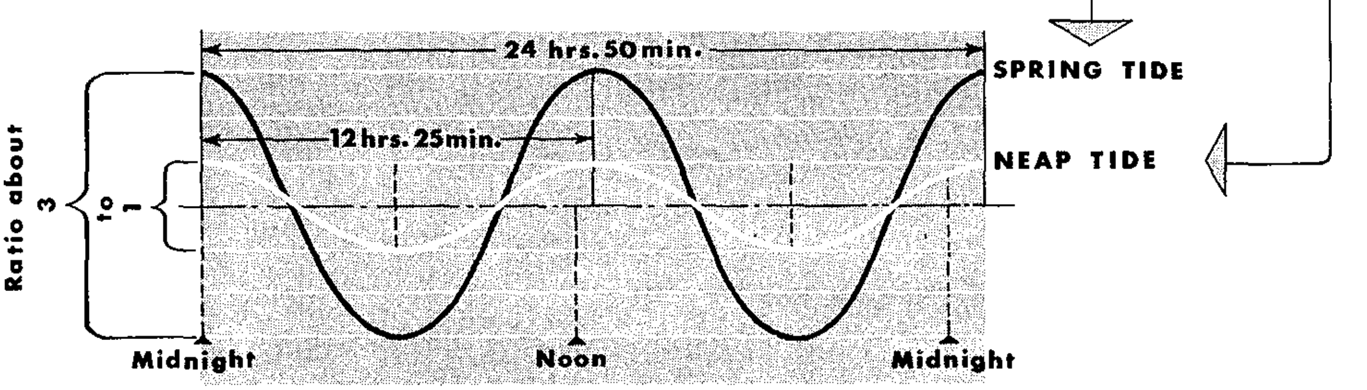


Diagram 4. **OCEAN TIDAL CYCLE**

SUN, EARTH, MOON AND THE TIDES

Figure 5

shape exactly opposite that of the football we should expect. Under the laws of resonance, the water, like the pendulum, takes a position or shape exactly the reverse of that toward which the moon is pulling at any instant: the shape of a tomato, squashed orange, or oblate ellipsoid of revolution whose short axis, normal to the axis of the earth, follows and always points toward the moon (fig. 5 - diag. 2). Were this not the case, tides at the Bay of Fundy and other middle latitudes would be inappreciable. The flat areas at the ends of the axis of the squashed orange form the two tidal troughs and the two halves of the bulge around the orange form the two wave crests of the tides at any given moment. Since the moon revolves around the earth in the same direction as the earth rotates on its axis, only much more slowly, a cork on the surface of the mid-Atlantic would rise on one or the other of these two wave crests every 12 hours and 25 minutes and make a complete rotation around the earth's axis every 24 hours and 50 minutes with respect to the moon. This fact is fundamental to the economics of tidal power generation, for if power varied with the tides, workers in a factory using this power would have to come to work 50 minutes later each succeeding day. Tidal power of this sort obviously would not be economical to market.

Economics of tidal power are complicated even more by the fact that the sun as well as the moon raises tides in the oceans (fig. 5 - diag. 3). However, the sun, despite its enormously greater mass, is only about half as effective as the moon because it is much farther away. Every 28 days, at the time of new moon, the sun and moon lie in the same direction from the earth, and two weeks later, at the time of full moon, they lie in opposite directions. When either of these conditions occurs, that is once every fourteen days, gravitational attraction of the sun and moon reinforce each other and cause maximum or spring tides (fig. 5 - diag. 4). When the moon is at either quarter phase, when sun and moon subtend a right angle at the earth, their gravitational pulls oppose and partly neutralize each other, causing a minimum tidal range, or neap tides with ranges only one-third as great as spring tides. When the moon is new or full and simultaneously in perigee - the point in the moon's orbit closest to earth - tidal range is particularly great. Thus accurate computation of energy output of a tidal power plant over 12 months is first of all a problem in astrophysics.

Far out to sea, the water surface merely rises vertically and then subsides as each tidal bulge passes; but when the bulge approaches a coast it moves more slowly in the coastal shallows, forcing the water to flow horizontally inland under the difference in hydrostatic head, piling up on the shore and then receding. The height tides will reach is largely determined by the configuration of the coast. On open, exposed headlands it may be 6 to 8 feet and in nearly landlocked embayments such as the Mediterranean it is negligible.

In funnel-shaped estuaries shelving from shallows out toward the open ocean, however, the water piles up as it is crowded forward into the ever narrowing bays, setting up strong tidal currents. This brings about exceptional tidal conditions, such as those in the Bay of Fundy, where the highest tides in the world are found.

HARNESSING THE TIDES

The present study of a proposed tidal plant in Passamaquoddy and Cobscook Bays, and the tidal plant planned for construction on the La Rance River in France are not, of course, man's first attempts to put the tides to work. The tides were first employed in a small way in England and other Western European countries as early as the eleventh century when "tide mills" were used to grind corn. Dutch Colonists in America built several tide mills, one in Brooklyn as early as 1617. Two tide mills once operated in Saint John, New Brunswick, until they disappeared with the advent of the steam engine in the late 19th century. Plans for harnessing the tides appeared again in the early twentieth century, when a German engineer proposed a tidal power plant on the coast of the North Sea. After World War I, studies were made in England of the feasibility of harnessing the tidal estuary of the River Severn. As early as 1919, W.R. Turnbull of Saint John, New Brunswick, suggested that power could be produced from the great tides at the head of the Bay of Fundy.

Other areas where tidal power projects have been proposed or studied are the Bay of L'aber Vrach on the northern coast of Brittany, Mt. St. Michel in northeast France near St. Malo, the Gulf of San Jose and the mouth of the Deseado River south of the Gulf of San Jorge in Argentina, and in the Soviet Union the Kola Peninsula, the Mezen Gulf, and the Sea of Okhotsk.

The first large-scale study of potential power production in the Bay of Fundy was made in the early 1920's by Dexter P. Cooper, known today as the "Father of Quoddy." His plan found support during the administration of President Franklin D. Roosevelt, who himself had summered at Campobello Island off Passamaquoddy Bay.

It is axiomatic that where the tides are highest, the potential power source is greatest. In the Minas Basin and Chignecto Bay in Canada, at the head of the Bay of Fundy, the tides reach an extreme range of 60 feet. Passamaquoddy tides near the mouth of the Bay of Fundy range from about 12 feet at neap tide to 26 feet at spring tide, with an average range of 18.2 feet. About four billion tons of water flow into and out of Cobscook and Passamaquoddy Bays twice each day. This is nearly equal to an average two-week flow of the Mississippi River below the mouth of the Red River above New Orleans, the accumulated runoff from almost half of the total three million square-mile land area of the United States. If only a fraction of this great volume of water could be harnessed to drive turbines, the resulting power would be impressive.

Tidal power, basically the same as any other type of hydro-power can be produced by passing water from a higher to lower elevation through hydraulic turbines. In this way the tides could produce power unaffected by droughts, floods, ice-jams, or silting which decrease the output and limit the life of river hydro plants. Moreover, ocean tides constitute the most dependable continuing source of terrestrial energy and, unlike the flow of rivers, can be predicted with accuracy. Their principal disadvantage is that four times a day the tide reverses direction. To devise a workable and economically feasible method of producing continuous power from such a varying flow constitutes the prime engineering challenge of tidal power production.

Of the many ways to produce power from the tides, the generation of large amounts of power requires one or more storage pools. A single pool may store water at high tide and discharge through turbines to the ocean at low tide, or it may be emptied at low tide to receive turbine discharge during high tide. Two separate pools may be used, one filled at high tide and the other emptied at low tide, with the high pool discharging through the turbines into the low pool. Various combinations of these methods alone or augmented by a pumping cycle may be used. Two conditions must in any case be met for economical power production: tidal range must be great enough to run turbines, and topography must permit economical construction of pools. The Passamaquoddy-Cobscook Bay areas in Maine and New Brunswick fulfill both conditions by providing a fortuitous combination of large, natural bays on a coast where high tides occur. A number of single and double pool schemes were analyzed to determine the method of operation best suited to Passamaquoddy and Cobscook Bays.

Single Pool Concepts. Figure 6 illustrates three methods of using the combined 146 square mile area of Quoddy and Cobscook Bays as a single pool under the mean tidal range at Eastport, Maine, of 18.2 feet, with 320" discharge diameter, fixed-blade propeller type turbines operating at 40 r.p.m. In the single-high pool plan no power is generated while the pool is filling at high tide, nor does generation start until the tide has fallen six feet below pool level. Power generation ceases when rising tide and falling pool level again reduce the head to six feet. However, net increase in power can be gained by pumping into the pool with reversible turbine-generators operating as motor-driven pumps during that portion of the cycle when no power is being generated. The operation of a single-low pool reverses the process and power is generated by flow from the ocean to the pool. The slightly smaller area of a single-low pool yields slightly less energy than an equivalent single-high pool with or without a pumping cycle. Power from a single-mean pool is generated by inflow through the turbines at high tide and by outlfow through them at low tide. Since a single-mean pool operates at a lower head than either of the other types of single-pool plan, its peak power and energy output

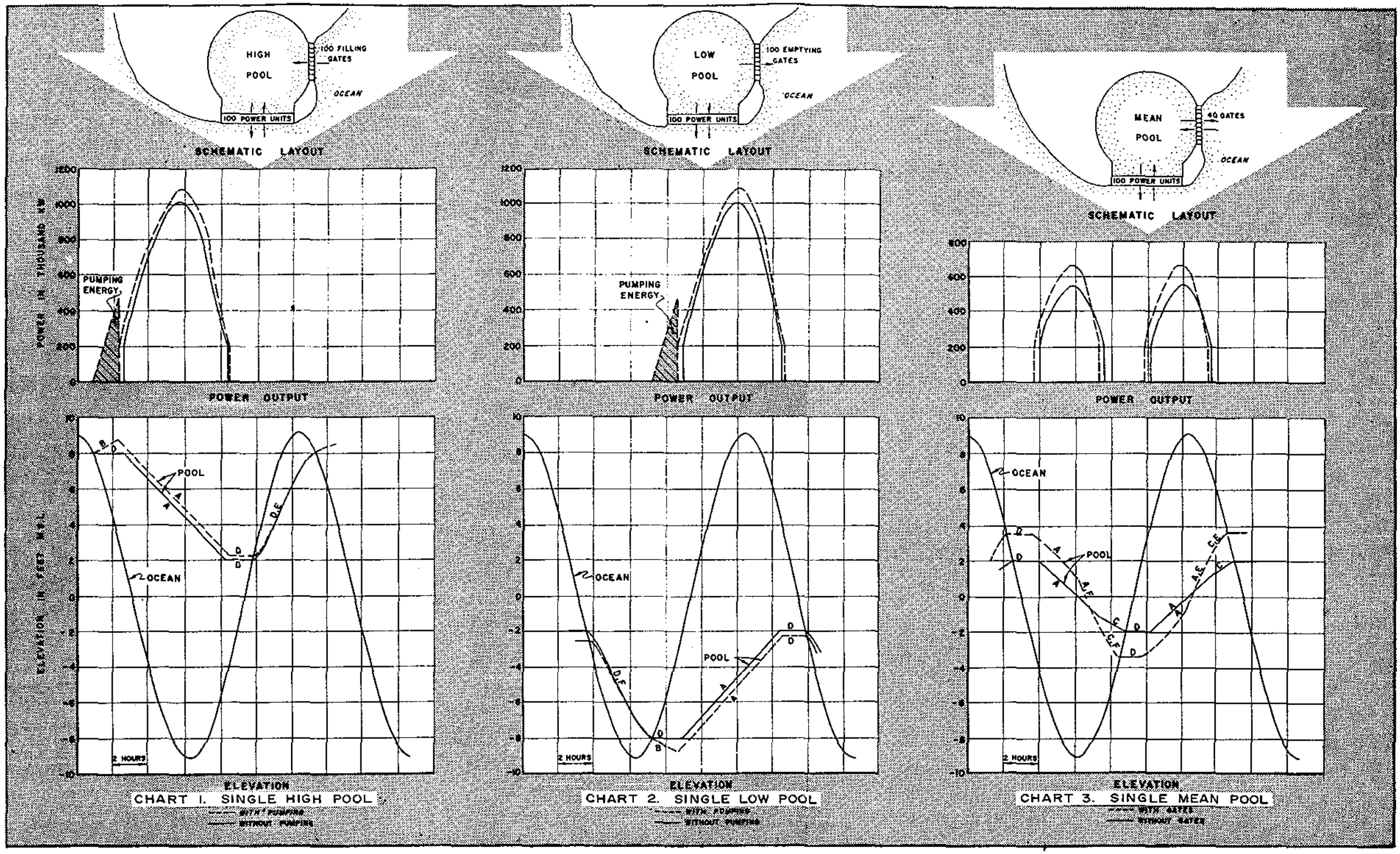


Figure 6

LEGEND

A	POWER UNITS AS TURBINES
B	POWER UNITS AS PUMPS
C	POWER UNITS AS ORIFICES
D	POWER UNITS INOPERATIVE
E	FILLING GATES OPEN
F	EMPTYING GATES OPEN

TIDAL POWER PROJECT

SINGLE POOL PLANS

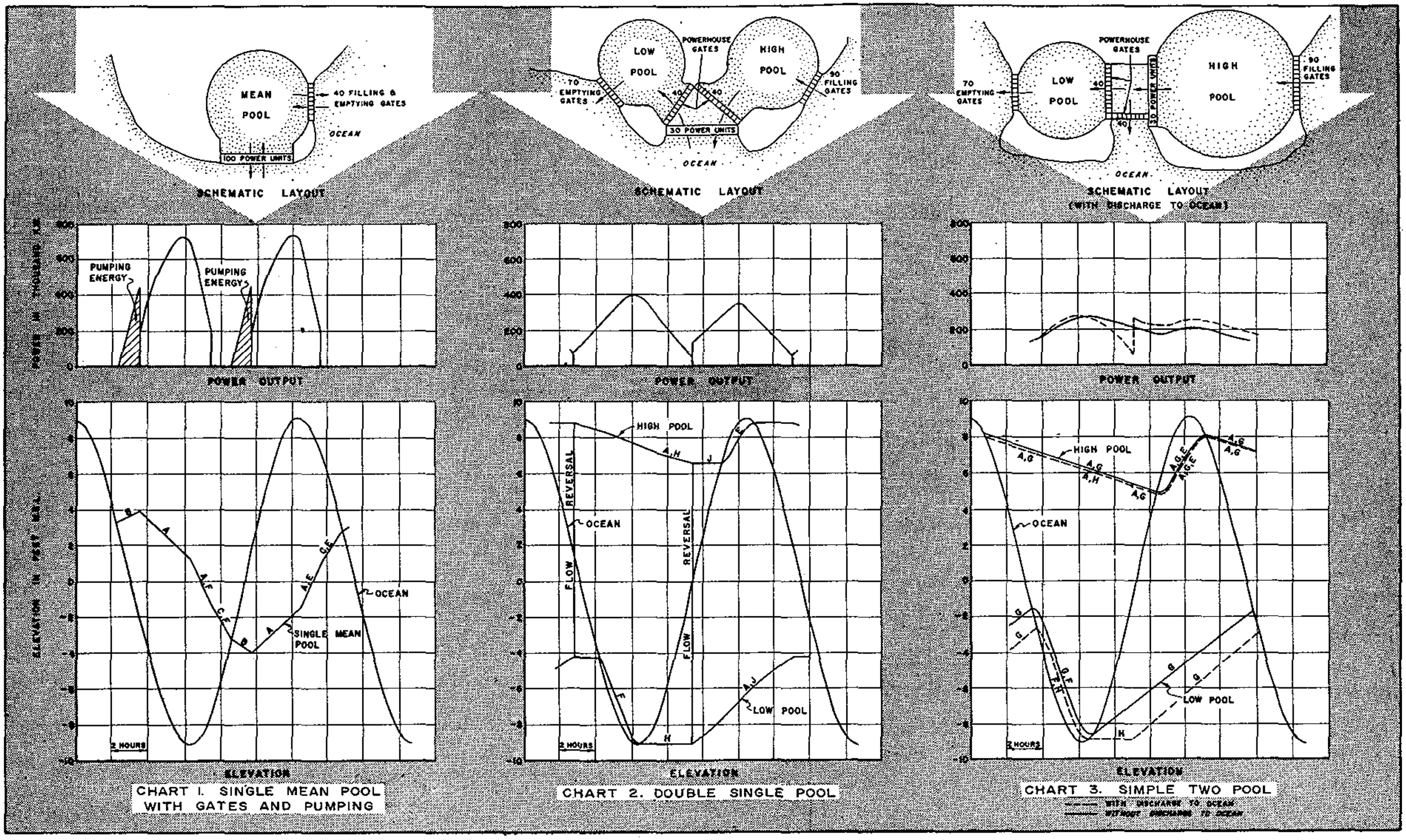
are less. Its output, however, may be increased by auxiliary gates (dashed line, fig. 6 - chart 3), as well as by a pumping cycle (dashed line, chart 1).

A unique combination of all three types of single-pool operation is under design by Electricité de France to harness the La Rance River on the Brittany coast. Special horizontal-axis turbo-generators used in this project are capable of producing power from flow in either direction, as well as operating as pumps or gated sluices discharging in either direction. The motor-generator is installed in a bulb-shaped housing in the center of the water passage in line with the horizontal axis of the turbine. Power from the La Rance project will feed into the existing high-capacity grid system of Electricité de France, where the intermittently generated power can be effectively absorbed. The special reversable-flow, turbo-pump generators will permit operation of this project as a single-high pool, single-low pool, or single-mean pool at will.

Two Pool Concepts. The principal disadvantage of any single-pool plan is the inability of the power plant to generate continuously. Where topography permits construction of two adjacent pools a single-high pool and single-low pool may be operated in conjunction through a common powerhouse (fig. 7 - chart 2). Gates between the power-house and each pool permit power generation by flow both from the high pool into the ocean and from the ocean into the lower pool. Power interruptions occur at times of change-over from one pool to another.

This disadvantage is avoided in the simple two-pool plan, which consists of a high pool filled at high tide, a low pool emptied at low tide, with a powerhouse between the two pools through which flow from the high to the low pool generates continuous but fluctuating power. As indicated by the solid line on chart 3 of figure 7, turbine discharge in a simple two-pool plan raises the level of the lower pool and lowers the level of the upper pool, thus progressively reducing the head and consequently the power and energy output. By diverting the tailrace flow directly into the ocean from the moment the emptying gates are opened until the moment rising tide and falling upper pool reduces turbine head to the minimum allowable, the lower pool may be maintained at a lower level with a consequent gain in power and energy. This type of operation requires two sets of tailrace gates which must be opened and closed against an unbalanced head. Hydraulic losses at these gates, unless the gates are very large, tend to offset energy gained by this modification of the simple two-pool plan. However, the evident advantages of producing continuous power make the simple two-pool plan far superior in most cases to any of the other plans which appear possible. The analysis outlined later in the paper reveals the superiority of the two-pool plan for conditions at Passamaquoddy.

Figure 7



LEGEND

A	POWER UNITS AS TURBINES
B	POWER UNITS AS PUMPS
C	POWER UNITS AS ORIFICES
D	POWER UNITS INOPERATIVE
E	FILLING GATES OPEN
F	EMPTYING GATES OPEN
G	FLOW FROM UPPER POOL TO LOWER POOL
H	FLOW FROM UPPER POOL TO OCEAN
J	FLOW FROM OCEAN TO LOWER POOL

TIDAL POWER PROJECT

MODIFIED SINGLE MEAN POOL PLAN AND TWO POOL PLANS

PASSAMAQUODDY FIELD INVESTIGATIONS

Through a field office established in Eastport, Maine, early in the survey, investigations to select the best project layout were conducted. Among these investigations, which included aerial mapping, deep and shallow water drilling, land drilling, geophysical exploration, analyses of soils, and tide gaging, were several of the most costly and difficult undertakings of the survey. Deep-water drilling in great depths and high tidal velocities, and geophysical exploration employing newly developed sonic equipment were two such challenging tasks.

Deep Water Drilling. Foundation conditions were investigated to determine the optimum design and location of the powerhouse, navigation locks and high, rock-filled dams by taking earth and rock core samples at selected points in the bottom of the bays. Facing the unprecedented task of core drilling waters 300 feet deep swept by reversing tidal velocities of up to 6 feet per second, Brown and Root Marine Operators, Inc., of Houston, Texas, brought from the Gulf Coast a 240-foot barge equipped with a drilling assembly specifically for this job. A Failing 1500 drill rig with a 38-foot mast was mounted on a General Motors diesel truck located on a specially constructed drilling platform 26 feet above the barge deck. Horizontal alignment of the drill column was maintained through continuous control of four 1-1/4 inch steel anchor cables attached to individual winch drums. Vertical tide fluctuation was compensated by adjustment of drill stem lengths between the drill deck and barge deck levels. Drilling was performed through a 30-inch conductor pipe which extended from barge deck level to near water bottom. This large pipe substantially reduced the effects of transverse tidal currents on the long string of drill rods. With this equipment a total of 15 carefully selected deep-water borings and 6 shallow borings of undisturbed overburden and bedrock samples were secured for analysis. Technical properties of foundation soils, including direct and triaxial shear strength and consolidation characteristics, were determined in the field office laboratory in Eastport, Maine, operated under contract by Greer Engineering Associates, Montclair, New Jersey. Geophysical exploration with a modified fathometer augmented foundation data in a greatly expanded area.

Geophysical Exploration. Equally as challenging as deep-water drilling was the use of highly specialized sonic fathometer equipment to chart the bays and to correlate deep-water borings. A joint investigation by the U. S. Geological Survey and the New England Division of the Corps of Engineers in the summer of 1951 had established the reliability of low frequency fathometer soundings by comparing sonic data with borings in the water areas between Eastport and Lubec. The Geophysical Division of the Fairchild

Aerial Survey Corporation of California was engaged to chart the bottom in Passamaquoddy and Cobscook Bays and determine the nature and depth of overburden. Investigation was made with the Marine Sonoprobe developed by the Magnolia Petroleum Company of Dallas, Texas. This instrument emits a high energy, audio-frequency signal designed to penetrate underwater sediments and to record echoes from interfaces of overburden and bedrock. It was found that the Sonoprobe could not distinguish between rock and gravel; it could, however, distinguish marine clays. Since both rock and gravel would furnish an adequate foundation for rock-filled dams, the Sonoprobe furnished valuable information by delineating areas of unsuitable clay bottom.

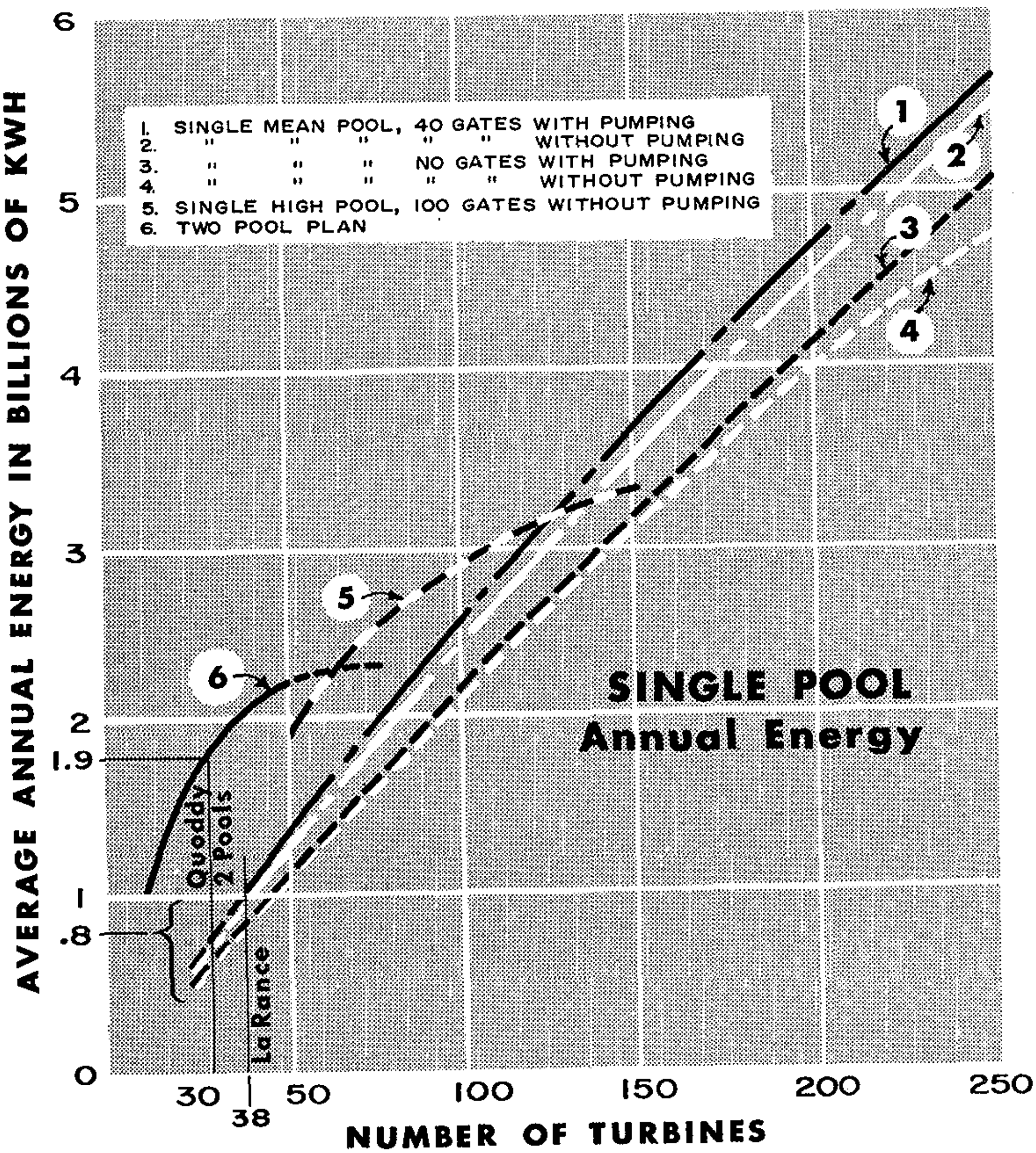
Correlation of data from these field investigations and laboratory tests permitted a relatively precise comparison of some 60 possible project arrangements to harness the power of the tides in Passamaquoddy and Cobscook Bays.

THE PLAN SELECTED FOR DETAILED DESIGN

The criterion for the optimum tidal project arrangement is that it should provide the maximum amount of energy (kw. hrs. per year) at the lowest cost. Each of the sixty possible schemes was tested against this criterion. Figure 8, in which the total number of turbines is plotted against annual energy in billions of kilowatt-hours for six typical project arrangements, is the key to this analysis.[1]

1. Based on an average tidal range of 18.2 feet (mean at Eastport Maine), pool area of 146 sq. mi., using 320-inch Kaplan turbines operating at 40 r.p.m.

Single Pool Plans. As shown on figure 8, a single-pool project requires more generating units to produce the same amount of energy as a simple two-pool project with the same gross pool area, unless the installation is larger than about 60 units. A single-high pool project like that shown on figure 6 - chart 1, with 50 power units and 100 filling gates, without pumping, would generate about 1.9 billion kilowatt-hours of energy per year, equivalent to the output of a 30-unit simple two-pool project with equal pool area. Though the simple two-pool plan would require 60 more gates and one more dam and lock than the single-pool project, it has 20 fewer power units. Since power units are a relatively large part of the cost, the single-pool project would cost about $50 million more than the simple two-pool project, increasing the power cost by 17 percent. Intermittent generation, and a 60 to 70 percent higher peak generation for the same amount of energy, also detract from the value of the single pool plan. Increasing the number of power units in the single-pool project from 50 to 100 would increase annual energy by one billion kilowatt-hours at a cost of about $215 million for the powerhouse alone, not including excavation and cofferdam costs. The high cost of this added energy ($0.215 per annual kilowatt-hour in powerhouse costs alone) clearly indicates the impracticability of a single-pool project of this size.



I. SINGLE MEAN POOL, 40 GATES WITH PUMPING
2. " " " " " WITHOUT PUMPING
3. " " " NO GATES WITH PUMPING
4. " " " " " WITHOUT PUMPING
5. SINGLE HIGH POOL, 100 GATES WITHOUT PUMPING
6. TWO POOL PLAN
SINGLE POOL
Annual Energy
AVERAGE ANNUAL ENERGY IN BILLIONS OF KWH
NUMBER OF TURBINES
Quoddy 2 Pools
La Rance
1.9
.8
30
38
0
1
2
3
4
5
6
50
100
150
200
250

Figure 8

Two Pool Plans. Next, the possibility of using two single-pools, one high and one low, equipped with reversible-flow La Rance type turbines in a common powerhouse was considered. Such a "single high - single low pool" project with 30 generating units would generate 7 percent more energy than the simple two-pool project. This increase is more than offset, however, by the loss of about 100,000 kilowatts of dependable capacity, increased complexity of operation, and the need for about 80 additional gates to permit connecting the powerhouse alternately to either of the two pools, and the interruption of power generation twice during each tide cycle in changing between high and low-pool operations.

It soon became abundantly clear from this type of analysis that while the single-pool plan and the "single high - single low" two-pool plan might produce more energy, they could yield only intermittent or interrupted power at higher cost than the continuous power of the simple two-pool arrangement.

The complex configuration of bays and islands in the Passamaquoddy-Cobscook Bay areas lends itself to numerous arrangements of the components of a simple two-pool project. Determination of the optimum arrangement, however, was complicated by the numerous possible combinations of filling and emptying gates and power units for each of 60 possible project layouts examined. A controlling factor in the search for the best arrangement of project components was that the more nearly equal the area of the two pools, the greater the energy output of the system.

The best project layout, the one which would produce the maximum amount of energy at the lowest cost, was determined by comparing total energy output to construction cost of each potential project layout. From generalized power curves (fig. 9) for the Eastport tidal conditions, the average annual energy generation could be determined for any project arrangement, once its pool areas, number of generating units, an number of gates were established. The construction cost was then estimated for all project components and the ratio of construction cost to energy output, or initial construction cost per annual kilowatt hours, was then computed for a number of layouts. The smaller this ratio, the more favorable the layout. As the study progressed, factors contributing to a low ratio were identified and used to develop more favorable arrangements.

Since the time required for manual computation of the annual energy output of each of the formidable number of possible project arrangements was prohibitive, these computations were performed electronically by digital computer. The General Electric Company's IBM 704, in Lynn, Massachusetts, affectionately known to its operators as the "high-speed moron," performed these complex calculations with astounding rapidity. Working at the rate of 40,000

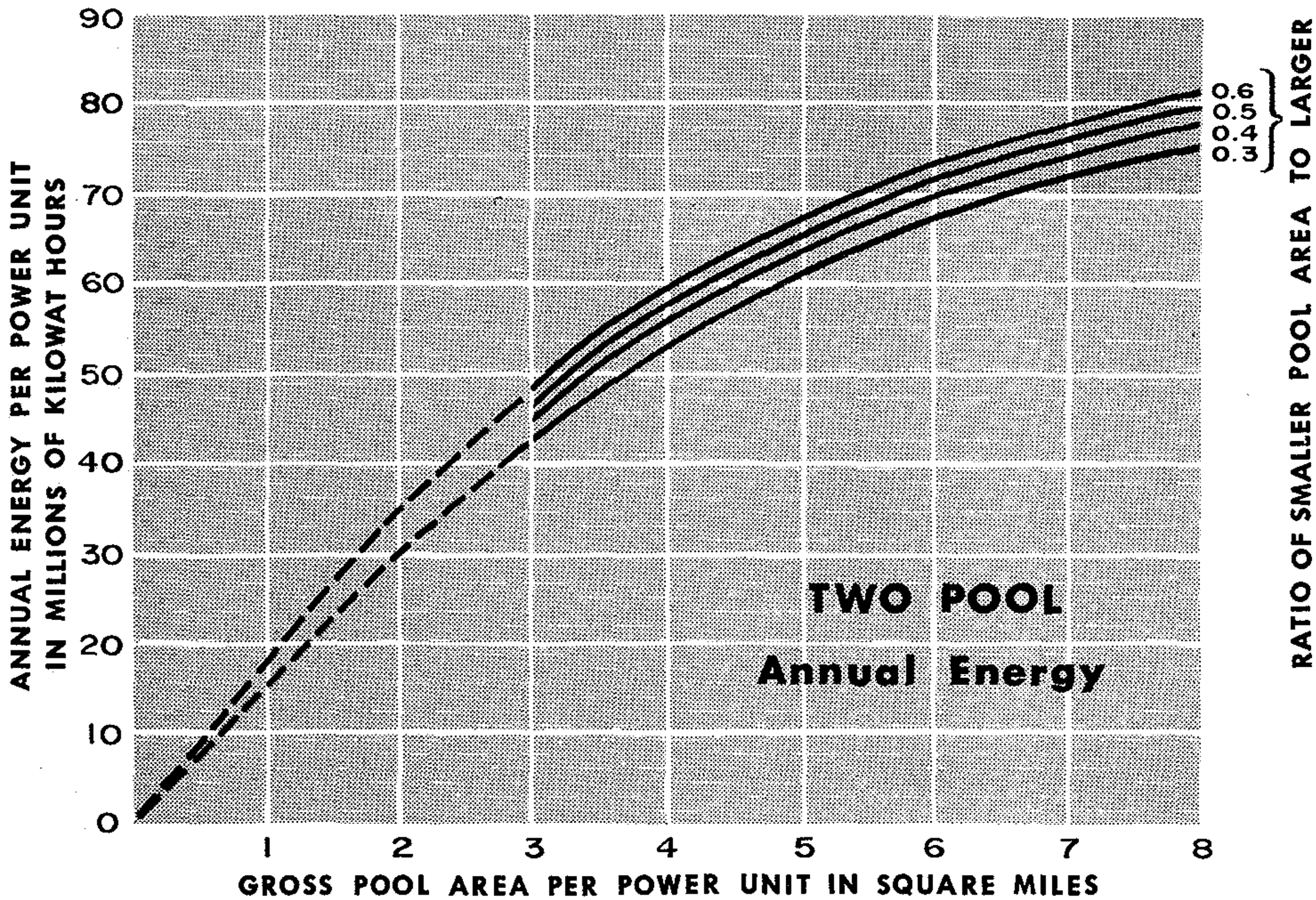

TWO POOL
Annual Energy
ANNUAL ENERGY PER POWER UNIT IN MILLIONS OF KILOWAT HOURS
GROSS POOL AREA PER POWER UNIT IN SQUARE MILES
RATIO OF SMALLER POOL AREA TO LARGER
0.6
0.5
0.4
0.3
0
10
20
30
40
50
60
70
80
90
1
2
3
4
5
6
7
8

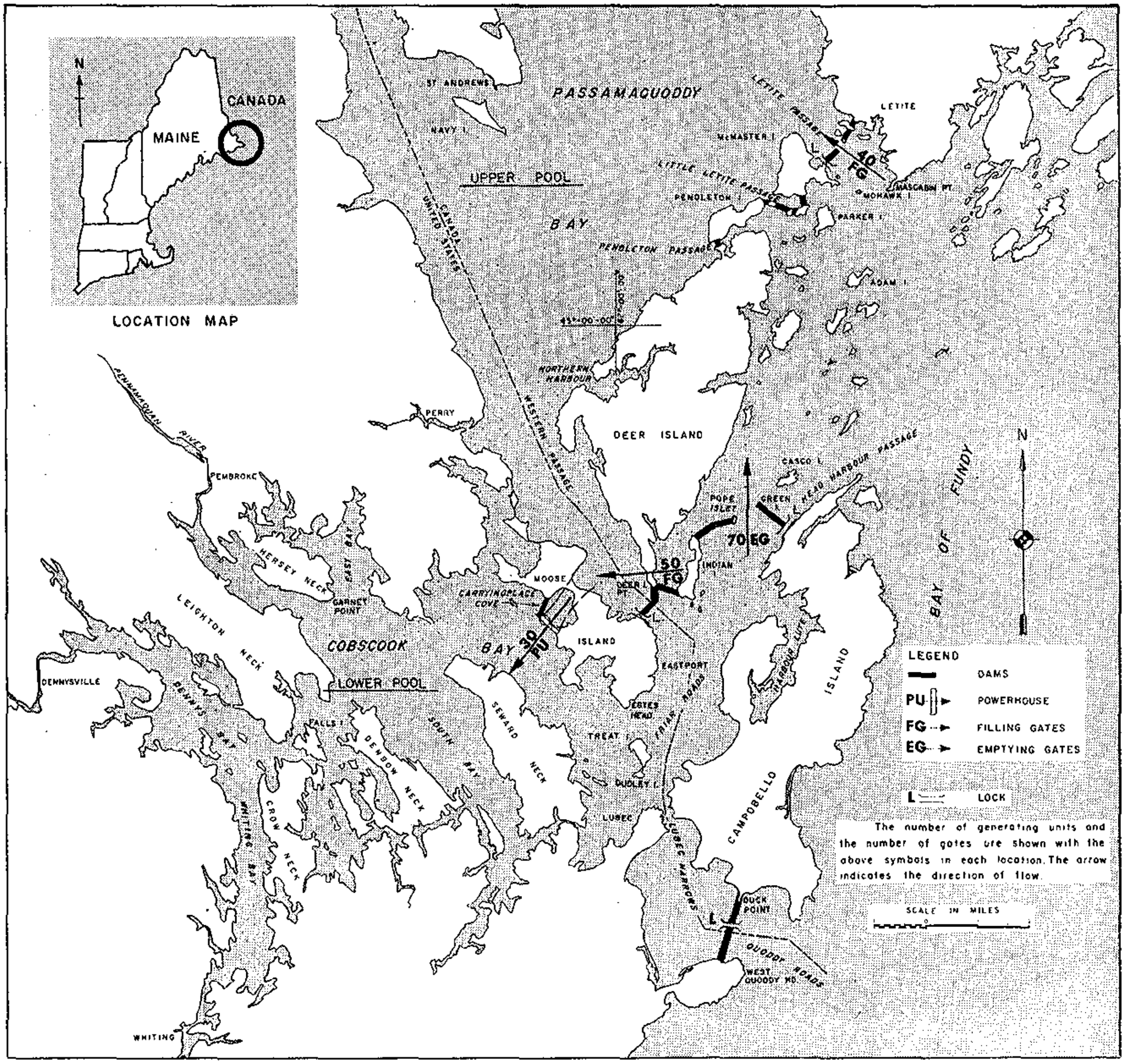
Figure 9

computations a second (with no coffee breaks), the "704" computed the energy output for one full month's operation in 4-1/2 minutes, a task which would take one engineer or mathematician, employing somewhat less accurate methods, a total of 15 days or 120 working hours. Even at $11 per minute, the "704" came up with the right answers at a great saving. Briefly, the kind of power problem programmed and fed into the computer was a gigantic equation involving 21 tidal cosine functions and other equations taking into account variations in tidal range, pool area and depth, filling and emptying head losses at the gates, and power output for a succession of complete cycles of flow from the upper to the lower pool. The solution to each problem gave the tidal energy output for a given number and arrangement of dams, turbines and gates over a period of 12 months. Since tidal hydro power is a function of the continuously changing head at each turbine, total annual energy output was determined by calculating the instantaneous power output at successive tidal stages and integrating for total energy over a twelve month period. A print-out made by the machine from a magnetic tape showed time, ocean elevation, upper and lower pool elevation, kilowatt hours produced in the interval, and accumulated kilowatt hours.

The arrangement which yielded maximum energy provided nearly equal upper and lower pool areas separated by a long, rock-filled dam extending from a powerhouse near St. Andrews, New Brunswick, across Passamquoddy Bay to Deer Island. Foundation exploration under Passamaquoddy Bay, however, revealed a 62-foot layer of soft clay which rendered construction costs of this arrangement prohibitive. At this point the optimum plan began to take shape.

From the topography and geology of the area, the lower cost of constructing a large, high pool and a small, low pool pointed unmistakably to the advantage of such an arrangement. To compensate for the disadvantage of lower energy yield from unequal pools, a double set of tailrace gates to permit the two-pool project to operate at times as a single high-pool was examined. The head loss through the additional gates and their cost of construction and maintenance however more than offset their modest energy increase. The economic advantages of the simple two pool arrangement with a large high pool and a smaller low pool nevertheless proved overriding and finally dictated its selection as the basis for detailed design studies.

In broadest outline, the optimum project arrangement thus selected for detailed design included the 100 square miles of Passamaquoddy Bay as the high pool and the 38 square mile area of Cobscook Bay as the low pool, with the powerhouse located at Carryingplace Cove as shown in figure 10. It involved a total length of earth and rock-filled barriers of about 28,000 feet, with a depth in some areas as great as 290 feet below mean sea level. Its 90 filling gates were incorporated in the barriers across Letie Passage and at Deer Point,



PASSAMAQUODDY TIDAL POWER PROJECT

PLAN SELECTED FOR DETAILED DESIGN

Figure 10

its 70 emptying gates in the barrier between Pope Island and Green Island; barriers at Quoddy Roads, and between Moose Island, Deer Island Point, and Indian Island closed the lower pool.

The selected two-pool project would generate about 1.9 billion kilowatt-hours a year using thirty 10,000 kilowatt generators. Generation would thus be 6000 kilowatt-hours per year per kilowatt of capacity. Average use of each kilowatt of capacity would be about 69 percent. Operation of this project would be continuous, with some capacity available at all times.

COMPONENTS OF THE PROJECT SELECTED FOR DETAILED DESIGN

With the major aspects of the project layout determined, it remained to carry design of each component of the selected plan - tidal dams, filling and emptying gates, navigation locks, turbines and generators, and the powerhouse - to a point which would permit accurate cost estimates.

Tidal Dams. The construction of some five miles of rock-filled dams in 300-foot channel depths with reversing, 5-knot tidal currents poses engineering problems without precedent. The difficulties of closing the barriers in the face of restricted and greatly increased velocity heads, and the incorporation of enough gravel and fines with the derrick stone to make a tight structure, appeared at first to be insurmountable. Construction methods and causes of recent foundation failures of the Great Salt Lake causeway for the Southern Pacific Railroad were studied, and hydraulic model tests are currently being conducted by Dr. Lorenz G. Straub at the University of Minnesota. Although Dr. Straub's studies are not yet complete, it appears from preliminary analysis that the dams can be built with conventional marine and land equipment. To overcome the problem of augmented tidal velocities during construction, formation of the dams can be programmed so that filling and emptying gates would handle part of the tidal ebb and flood. How the dams can be made sufficiently watertight to avoid power loss is another difficulty not yet resolved. Although some 18 million yards of clay must be excavated in the forebay of the powerhouse, it does not appear possible to use it as an integral part of the rock-filled dam since there is no apparent method of compacting this clay under water.

Filling and Emptying Gates. The selected plan calls for 90 filling gates, 40 in Letite Passage and 50 at Deer Island Point, as shown on figure 10. Comprehensive study of all types of gates, leading to detailed examination of nine of the most feasible, led to selection of a 30' x 30' vertical lift gate set in a venturi throat, as illustrated in figure 11. The venturi throat permits maximum velocity head and discharge rate for a given gate area. To avoid icing, the gates are set low enough to inundate the upper-pool side permanently and the ocean side at all times but at extreme low tide. Early in the study

VERTICAL LIFT FILLING GATE IN SUBMERGED VENTURI SETTING

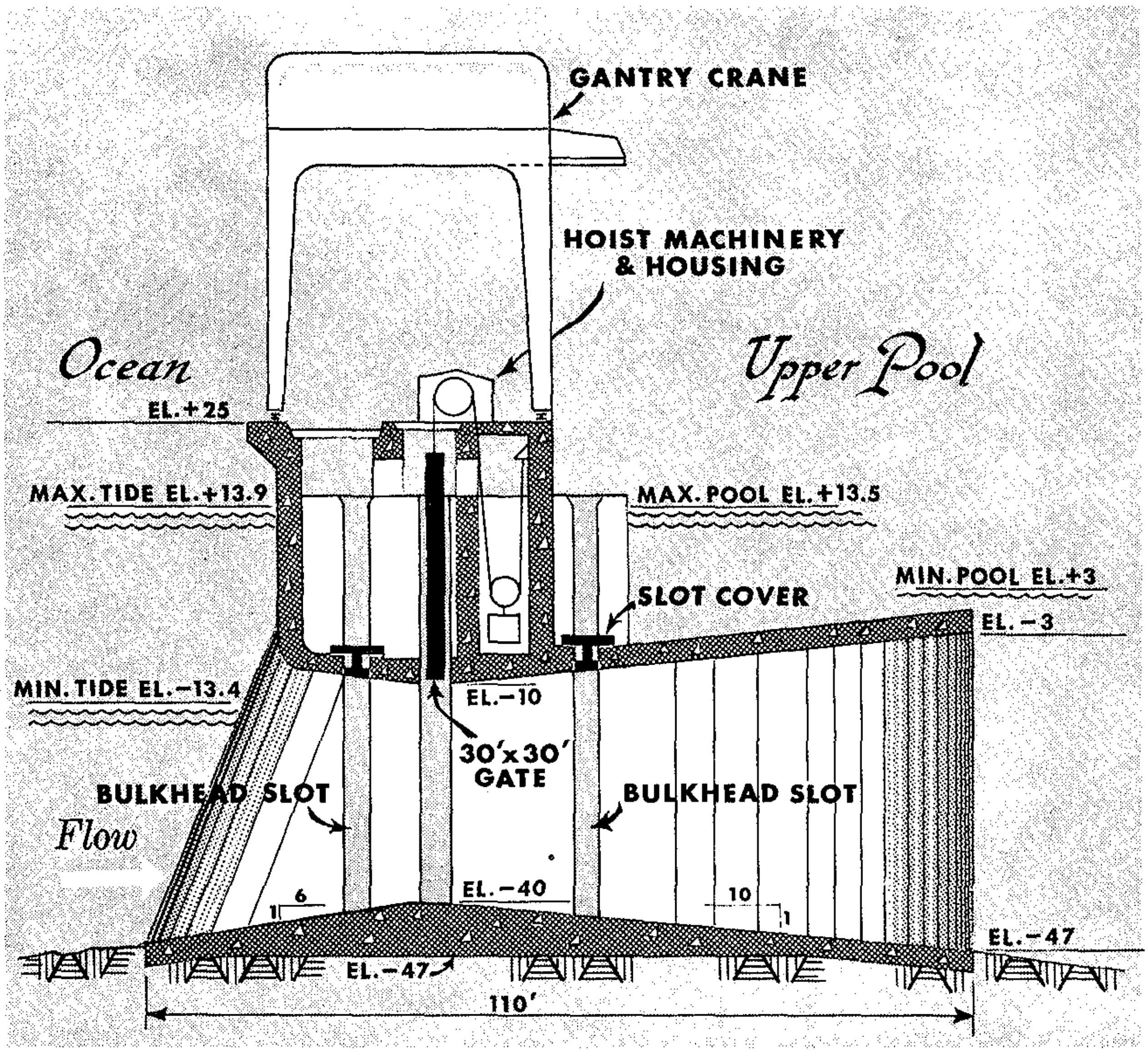


Figure 11

a crest gate with a vertical-lift leaf appeared to promise economy because of high flow capacity, but the costs of auxiliary structures and maintenance to prevent icing more than offset its lower construction cost and superior hydraulic capacity. Accordingly, detailed design of the submerged vertical-lift gate in a venturi setting will be completed for cost estimates of the selected plan.

In the reach between Polk and Green Islands 70 emptying gates, similar to the filling gates but set at a lower elevation, will empty the lower pool. The cofferdams required for construction of filling and emptying gates, as well as for the navigation locks and the powerhouse, will be subjected to heads as high as 60 feet, whereas the heads on the completed structures will not exceed 26 feet. A special study now under way indicates that the problem of cofferdam construction, although challenging, will not prove insurmountable.

Navigation Locks. Four navigation locks are planned for the selected tidal project. Two sets of locks at Letite Passage and Quoddy Roads at the extreme north and south limits of the tidal project have clear dimensions of 95' x 25' x 10' to pass smaller fishing vessels. Two sets of locks at Head Harbor Passage immediately east of the emptying gates and at Western Passage to the north of Eastport, have clear dimensions of 415' x 60' x 21' to pass vessels somewhat larger than the present traffic. Reversing head on the locks ruled out the use of miter gates in favor of sector gates, which have proved successful under somewhat similar conditions at numerous locks on the Intracoastal Waterway in the Gulf of Mexico and on the Sacramento River where similar head reversal occurs. The sector gate was thoroughly tested at the Waterways Experiment Station at Vicksburg, Mississippi, for the Algiers Lock on the Intracoastal Waterway, Gulf Section, Louisiana. Locks can be filled through partly opened sector gates supplemented by short culverts in the gate monolith, a method particularly advantageous in the selected tidal power project. Long filling culverts will not be needed and wall construction in the rock cut, encountered to various depths at all lock locations, will be held to a minimum.

Turbines. The low average power head of about 12 feet of the selected two-pool tidal power project dictated the selection of turbines with a throat diameter as large as practicable in a powerhouse of minimum length to fit the available sites. Manufacturing specifications and other factors pointed to a maximum diameter of 320 inches and a minimum rotation speed of 40 r.p.m. Performance characteristics for fixed-blade propeller turbines and Kaplan turbines furnished by United States, Canadian and European manufacturers indicated that the greater energy of the Kaplan was offset by its higher cost of manufacture and operation and maintenance in sea water. The new type of turbine recently developed in Europe and adopted for use at the La Rance single-pool tidal project in France was also studied for possible adaptation to the Passamaquoddy project. Representatives of the Société Grenobloise D'Études et D'Applications Hydrauliques recommended these units as more efficient than conventional units. Power studies show that the bulb-type turbines develop about as much power as the Kaplan. Structural studies indicate that a saving of approximately $400,000 per powerhouse unit might be realized if this type of unit were used, although this saving probably would be offset by the need to compensate for the low rotative inertia charactertistc of these units. For this reason, and because of the novelty of the bulb-type unit (only one such large unit has been extensively tested in the Massive Centrale), unresolved maintenance problems and other questions, the bulb type unit was abandoned in favor of the conventional fixed-blade type for the purpose of evaluating project feasibility.

Generators. Generators rated at 10,000 kw., with a 15 percent overload capacity, direct-connected to 40 r.p.m. turbines were selected in preference to more costly larger generators. The increase of generator speed by a geared speed increaser developed excessive tooth pressures and proved infeasible.

The Powerhouse. Selection of the turbine and the dimensions of its water passages permitted preliminary design and cost estimates for the powerhouse by Stone & Webster Engineering Corporation of

Boston, Massachusetts. The outdoor powerhouse, shown in the architect's rendering (fig. 12), has two erection bays at each end and two large travelling gantrys for erection and maintenance of turbines and generators. All control equipment is located on the turbine room floor below the top deck, with the main transformers on the upstream side of the powerhouse connected to the switchyard at the far (north) end by means of oil-filled high voltage cables. The 30 generators are connected to 4 output transformers, two operating at 230 kilovolts for supply to the United States and two at 139 kilovolts for Canada.

FLUCTUATING TIDAL POWER AND AUXILIARY SYSTEMS

The problem of stabilizing the fluctuating power output is crucial to any tidal power project. Figure 13 shows how the output of the selected two-pool project varies with the ebb and flood of the semi-diurnal tides. Coupled with the variation from spring tide to neap tide and the fifty minute daily lag, this variable output contrasts sharply with the pattern of normal power demand which follows the peak demands of the Monday to Friday work week. Unless a great deal of the tidal energy is to be wasted, tidal project output can be modified only slightly to match the characteristic load pattern. Some way must be found to reconcile the difference between these two patterns. This problem common to all tidal power projects, admits of several possible solutions:

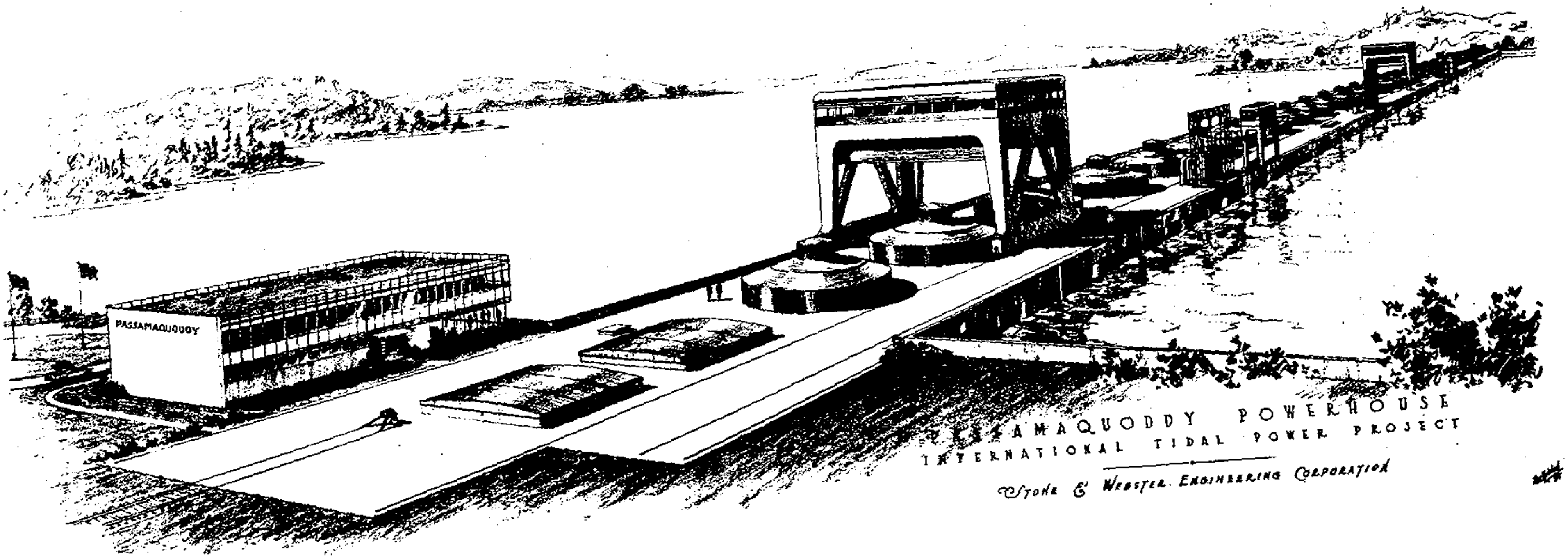

PASSAMAQUODDY
PASSAMAQUODDY POWERHOUSE
INTERNATIONAL TIDAL POWER PROJECT
STONE & WEBSTER ENGINEERING CORPORATION

Figure 12

TYPICAL CYCLE OF TIDAL PLANT OPERATION

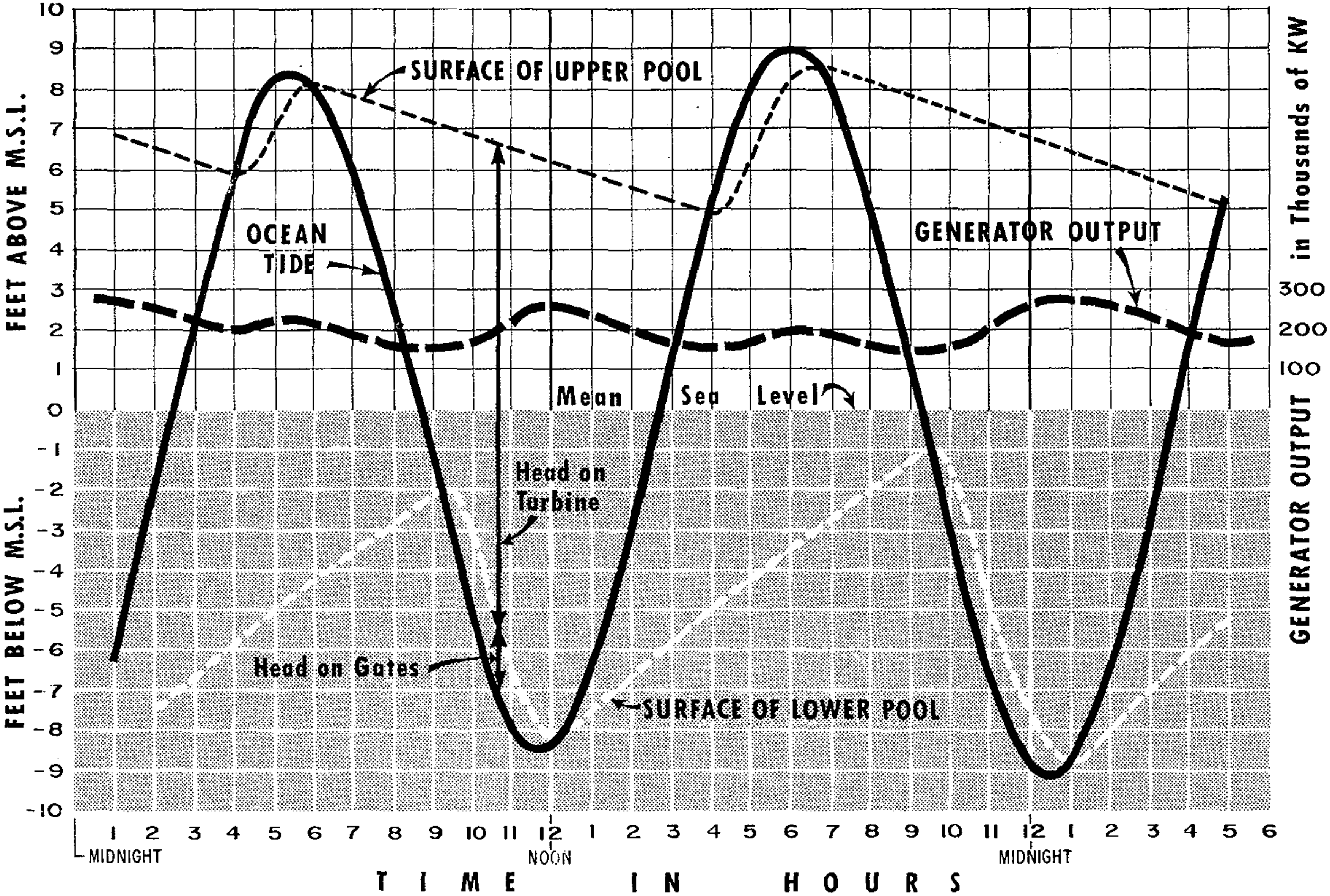


Figure 13

First, if tidal energy were fed into a sufficiently large power grid, as Electricité de France plans for the output of the La Rance Project, the remainder of the system could absorb the difference between the load and tidal plant output.

Second, tidal power could be supplemented by a steam-electric plant. However, since the auxiliary output must vary rapidly from hour to hour, and since its energy output per kilowatt of capacity would be relatively small, a steam-electric auxiliary appears highly uneconomical.

Third, tidal power could be supplemented by means of a pumped storage plant. Using power from the tidal plant at times when it is not required to meet load demands, water could be pumped to a higher storage basin and released through turbines as required to meet the load. Since the tidal plant alone would generate about 1.9 billion kw.hr. during an average year, with the rate of output varying from 100,000 kw. to 345,000 kw., or an average rate of 217,000 kw., a pumped-storage plant with 225,000 kw. installed capacity would stabilize the combined project capacity at 325,000 kw. The use of either the steam-electric or pumped-storage plants as an auxiliary power source would, however, increase the gross cost of the tidal power considerably. Two of the most favorable pumped storage sites have nevertheless been investigated and a site on the Digdeguash River near its outlet into Passamaquoddy Bay east of St. Andrews has been adopted for detailed study. Useable pumped storage would amount to 198,000 acre feet, or about 32 million kw.hr. of potential energy. A loss of about 130 million kw.hr. of tidal energy a year in the pumping and generating cycles would be partially offset by 33 million kw.hr. per year of fresh water inflow from the Digdeguash drainage area. At a 60 percent capacity factor (the ratio of firm power to peak power), a dependable capacity of 325,000 kilowatts is attainable by this means.

Fourth, among a number of river hydro sites examined, Rankin Rapids on the upper Saint John River has been selected at the site for the optimum combined river hydro and tidal plant project. This site could be developed to provide 2.8 million acre feet of useable storage, which will give almost 100 percent regulation of the river and generate about 1.1 billion kw.hr. of electrical energy annually. A powerhouse of 8 units rated at 50,000 kw. each would provide a plant capacity factor of 27 percent and an overall project capacity factor of about 60 percent. Rankin Rapids operated in conjunction with the tidal plant, by substantially reducing the gross cost of project power, thus appears to be by far the most promising and economical combined project.

PROJECT EVALUATION

Just as any sound economic enterprise depends for its survival upon revenues exceeding cost, so the constitutional basis of any federal program domestic or foreign, contemplates that the broad benefits to the nation shall exceed the cost to the taxpayer. Accordingly, the economic justification of the Passamaquoddy Tidal project will depend upon whether the tidal power project is more economical than other available methods for developing power. The degree of economic justification will be measured by the ratio of annual costs to annual benefits. Benefits from the tidal power project will be determined by comparing its power cost with the cost of generating an equivalent amount of power by cheapest alternate means, probably a steam-electric plant. The cost of a kilowatt of installed capacity and a kilowatt hour of energy of the tidal plant will be compared to similar costs of an equivalent steam plant. Cheaper tidal plant costs would support a favorable recommendation. Annual costs for the tidal project and its auxiliary component will include interest on, and amortization of, the initial investment over the life of the project and the annual cost of operation and maintenance. The initial investment will include construction cost, allowance for contingencies, engineering, supervision and overhead allowance and interest during construction. The capital investment will be amortized over the fifty-year normal project life of Federal Civil works projects. Differences in construction costs and benefits and interest rates between the two countries suggest that a separate benefit-to-cost ratio be computed for each. This would enable each country to determine whether the contribution required of it for construction of the tidal project would be justified by the benefits. Should the economic analysis prove favorable - that is, if Quoddy power with or without auxiliary proves cheaper than steam-electric power in the area, it would still remain to determine whether present and potential power markets in Maine and New Brunswick could absorb so large a block of power were it available. Accordingly, the New Brunswick Electric Power Commission and the Federal Power Commission have conducted power market surveys of the potential consumers of Quoddy Power in the Maine-New Brunswick areas.

ECONOMIC AND POWER MARKET SURVEYS

Power Markets in Maine. Power markets in Maine consist of rural, urban, residential, commercial, industrial and other electric energy consumers served by utility systems. In addition, some industries are supplied by their own individual power plants. In 1956 utility requirements amounted to 2,591 million kilowatt-hours, with a combined peak demand of 483,000 kilowatts. Generation by non-utility plant in 1956 amounted to 1,557 million kilowatt hours.

Requirements for utility-furnished energy is influenced directly by increases in population, higher use of energy per customer, expansion of industrial, trade and service activities, and the introduction of new uses of electric energy. The aggregate effect of these factors is a sustained growth of the demand for electric power and a continuing need for additions to the power supply facilities of the utility systems. Quite different is the growth of generation by non-utility power plants which are built and operated by industrial firms to provide power and process steam, or to utilize low-cost by-product fuel. Their expansion, as well as the construction of new industrial power plants, takes place only when this is more economical than the purchase of utility power. Past experience shows that the growth of non-utility generation is slow and irregular. Thus consumers in Maine who could use power from the proposed project in a definite and predictable way are those now served by utility systems, which are certain to continue to grow for many years to come. New industries which might be attracted to the vicinity of the tidal project will reduce the amount of power which otherwise would be available to meet the utility load. Between 1940 and 1955, energy requirements and peak demand increased by 117.9 and 126.8 percent, respectively. By 1980, energy requirements will reach an estimated total of 7.53 billion kilowatt-hours and a peak demand of 1,380,000 kilowatts. A gradual and slow improvement in annual load factors is expected to develop as the result of increased energy use per customer and greater diversification of industrial activities in the State. Future energy requirements were estimated on the basis of continued industries, particularly those dealing with tourists and vacationists.

Power Markets in New Brunswick. Studies conducted by the New Brunswick Electric Power Commission show that the growth rate of future requirements in New Brunswick will be higher than that of Maine. Inasmuch as 1955 requirements of Maine represent a higher and a more advanced level of electrification than in New Brunswick, a more rapid growth of power requirements in New Brunswick is to be expected from industrialization of the Province and exploitation of its large mineral resources. The largest utility system in the Province is operated by the New Brunswick Electric Power Commission, whose service area is adjacent to the tidal plant. In 1955, the energy requirements of the New Brunswick Electric Power Commission amounted to 467 million kilowatt-hours. According to estimates prepared by the Commission, these requirements will increase to 3,029 million kilowatt-hours in 1980. Direct retail sales, which amounted to 72 million kilowatt-hours in 1955, or 15.4 percent of total energy requirements, are expected to increase by 1980 to 1,013 million kilowatt-hours, or about 14 times the 1955 figure, and to constitute nearly 33 percent of total requirements at that time. Industrial sales, which in 1955 aggregated 84 million kilowatt-hours will, as a result of the expected expansion of mining industries in the Province, increase by 1980 to an estimated 588 million kilowatt-hours, or more than seven times the 1955 figure. All other service classifications are expected to increase at fairly constant rates during the period under consideration.

Economic Surveys. Over and above the expansion of existing markets the possibility of attracting new industry to the area must be considered. The Arthur D. Little Corporation of Cambridge, Massachusetts, is conducting an economic survey of Maine to determine all possible potential uses for Quoddy power. One of the principal aims of this survey, which is yet to be completed and correlated with the power market studies, is to identify industries that might be attracted to the area by a new source of dependable power. An industrial development in the immediate vicinity would substantially reduce problems of transmission lines, auxiliary power, and load factors. A similar economic survey of New Brunswick is being conducted by the Department of Economics of the University of New Brunswick.

CONCLUSION

From the brief analysis at the beginning of this paper of the future world energy problem, the limitations of conventional and fission energy sources and the uncertainty of perfecting the thermonuclear reaction for man's use in the immediate future, tidal power generation certainly demands careful consideration. Although it is too early in the present survey to forecast what the recommendations of the Board and the International Joint Commission may be, it is of interest to look briefly into the future of tidal power.

The possibility has been suggested that drawing a fraction of the 2 billion horsepower from the tides might alter their resonant wave structure, just as the configuration of the standing waves on a power transmission line can be shifted by turning on a 5 ampere electric light. Dr. Arthur T. Ippen, Professor of Hydrodynamics at the Massachusetts Institute of Technology, is investigating this problem both from a theoretical and practical viewpoint.

Earlier in the paper it was stated that energy is being dissipated continuously through friction by tidal action at the rate of some 2 billion horsepower. This estimate is interesting not only in helping to forecast the maximum energy that might one day be derived from the tides, but also in shedding light on the question of satellite orbits and the future evolution of the earth-moon system, subjects much in the public eye these days. Tidal energy was estimated from the work of G. H. Darwin, son of the famous 19th Century naturalist, who found from the rather precise records of the earliest total solar eclipses by the moon that tidal friction has probably slowed the rate of rotation of the earth and thus lengthened our sidereal day by about 1/1000 of a second a century, the energy equivalent of 2 billion horsepower. The month has similarly lengthened, but at a slower rate, with the moon spiralling away from the earth. Ultimately, when the day and month become equal, the earth will always show the same face to the moon, just as the moon shows the same face to the earth today. At this time in the far distant future, one might take a trip abroad to see the moon. Darwin further predicts that when this equilibrium of the earth and its major satellite is upset by tidal friction caused by the gravity of the sun, the moon will then begin to spiral back toward the earth to a position somewhat nearer than at present, whereupon the entire process would be repeated.

The significance of Darwin's theory is that it is supported quantitatively by measurements of the actual amount of energy dissipated by the tides along the coasts. Apparently about 60% of the estimated 2 billion horsepower of energy is actually dissipated as friction along the coasts of the continents, leaving the 40% remaining to be accounted for in the major ocean basins. It can be shown from classical Newtonian physics that the rate at which tidal energy is generated by gravitational attraction of the moon and sun would not be affected by its conversion from mechanical (friction) energy into electrical energy. Even were it possible to convert all tidal energy into useful power, it is difficult to see how the rate of tidal energy generation or the configuration of the resonant tidal wave structure could be affected. Thus man can build as many tidal dams and powerhouses as he likes without anxiety that he might somehow upset the resonant wave structure of the ocean tides and thereby flood distant coastal cities, cause the moon to come tumbling down from the heavens around his ears or, alternately, to disappear somewhere into intersellar space.